A STUDY OF POROUS METAL COOLING

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A STUDY OF POROUS METAL COOLING

Thesis by

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and
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In Partial Fulfillment of the
Requirements for the
Degree of Aeronautical Engineer

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SUMMARY AND ACKNOWLEDGEMENTS

This investigation was conducted to study the flow rate necessary to maintain a sweat cooled metal at an equilibrium temperature when subjected to a high gas temperature. The study was limited to fundamental tests on copper, bronze, and stainless steel porous metal specimens which were the only types available at this time. Water cooling was used throughout the investigation.

Conclusions of a qualitative nature were obtained which show that water flow rate is a primary factor in maintaining sweat cooled metals at equilibrium temperature, and that metal thermal conductivity has but slight effect. The feasibility of the sweat cooling technique was proven by the fact that a water flow rate of less then 0.1 cc/in.^{2} - sec was required to satisfactorily cool a porous metal surface subjected to a potential heat transfer of 1.0 BTU/in.^{2}-sec.

The experimental investigation was conducted at the Jet Propulsion Laboratory of the California Institute of Technology from November, 1945 to May, 1946. The authors are indebted to Dr. Pol Duwez for his perfection and production of the porous metal specimens and for his direction and supervision in the line of research. They also wish to acknowledge the assistance of Mr. Lindsey Wheeler Jr. in the design and development of the experimental equipment and technique.

INTRODUCTION

The efficiency of jet propulsion power plants could be greatly improved if the materials used were able to withstand higher gas temperatures. Therefore a means of increasing the allowable maximum temperature limit will require development of higher melting point materials or cooling of the present day materials. One method of attack to improve cooling is the infiltration of a fluid through a porous metal. This type of cooling is known as "sweat cooling".

The term "sweat cooling" is applied to the process whereby a fluid is passed through a porous metal and forms a protective film of liquid or vapor on the surface exposed to a high gas temperature. This protective film may be attained by passing either gases or liquids through the porous metal. In view of the numerous experimental techniques of handling different coolants, this investigation was limited to a study of water cooling only.

The actual production of porous metals suitable for cooling purposes is in its infancy, and at the outset of this investigation only a limited number of metals had been successfully produced by powder metallurgy methods. The principles involved in the "sweat cooling" of these metals were unknown, but it was believed that the variables were: the temperature and velocity of the gas; the flow rate, temperature, viscosity, heat of vaporization, and vapor pressure of the coolant; the pore size, percent porosity, thermal conductivity, and temperature of the porous metal.

The purpose of this investigation was to conduct fundamental tests on the produced specimens. These experimental tests were restricted primarily to a correlation of water flow rate and heat transfer at a constant metal temperature. The actual value of heat transfer at the specimen could not be measured, therefore potential heat transfer values were obtained in the section immediately ahead and adjacent to the porous metal specimen. Potential heat transfer of a liquid cooled porous metal is defined as the heat transfer through a solid metal exposed to the same gas temperature and velocity.

EQUIPMENT

The apparatus used in this investigation consisted of a cylindrical chamber made up of a porous metal test specimen and a stainless steel tube which was cooled by a water jacket. An oxygen-acetylene flame with a temperature of approximately 3500°F and with a velocity of about 300 ft/sec. was passed axially through the cylindrical chamber. Variations in heat transfer values were attained by regulation of the oxygen and acetylene pressures to the burner, which, in effect, varied the flame temperature and velocity. In this manner heat transfer values as high as 1.2 BTU/in.^{2}- sec were easily obtained.

The porous metal specimens were supplied in a standard cylindrical form having an outside diameter of 1.85 in., and inside diameter of 1.05 in., with an overall length of 1.75 in. (See Fig. 1). The specimens were grooved at both ends to permit sealing in the test chamber by means of rubber gaskets. They were produced at the Jet Propulsion Laboratory by a powder metallurgy technique developed by Dr. Pol Duwez.* Three different types of porous metals were studied, namely; copper, bronze, and stainless steel. The descriptions and specifications of these samples are tabulated in Table I.

The specimen Test Assembly was constructed of stainless steel and consisted of three major components: 1. specimen holder, 2. entrant section, and 3. burner clamp. This assembly is shown in Fig. 2. The

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*Dr. Pol Duwez: CALCIT report to be published

specimen holder consisted of a water jacket and permitted the metal specimen to be inserted from the rear and sealed from the water jacket by means of rubber gaskets and permatex. The holder was clamped to the entrant section with an asbestos gasket used as a seal. The entrant section was surrounded by a water jacket from which heat transfer values were obtained. This water jacket was divided into two parts. In order to obtain the heat transfer as close as possible to the test specimen, the forward part of the jacket only was used for the heat transfer measurements. The rear water jacket was used solely to prevent overheating of the entrant section. The burner clamp held the oxygen-acetylene burner in place which permitted the flame to pass axially through the entrant section and specimen holder. The complete test assembly was mounted as shown in Figs. 3, 4, and 5.

The pressure around the porous specimen was maintained by a water head which could be varied up to a value of approximately 15 ft. The actual water flow at any head could be observed by use of the glass reservoir and fixed scale. (See Fig. 3).

The water flow through the forward part of the entrant section was measured by a Cochran Float type flowmeter. The water inlet and outlet temperatures for this flow were obtained by use of two thermocouples mounted in the water connections to and from the forward water jacket. These thermocouple leads were connected with the selector switch. (See Fig. 4).

In order to determine the inside wall temperature of the specimen it was necessary to insert a thermocouple through the test sample from

the side. A one-eighth inch hole was drilled from the water jacket side of the specimen to within one-sixteenth inch distance from the inside wall. This hole was used to accommodate a wooden plug containing the two thermocouple wires. A small hole was then drilled the rest of the way through the specimen to just permit the thermocouple bead to extend flush with the inside surface. The swelling of the wooden plug in contact with the water in the jacket was found to seal the thermocouple in place. The thermocouple wires were lead out through a hole in the specimen holder, (See Fig. 2), and connected to a selector switch. (Fig. 3 and 4).

A Leeds and Northrup potentiometer Model 8657-C was used to obtain the temperature from the chromel-alumel thermocouples. This instrument had a guaranteed error which was less than plus or minus .05 millivolts.

OPERATING PROCEDURE

The operating techniques and procedures applicable to porous metals were unknown at the outset of this experiment. As a consequence the operating procedure and experimental equipment were modified to a large extent throughout the investigation, and much time was spent in devising an appropriate technique.

The original test runs were made with a retracted burner which permitted outside air to enter into the combustion process within the assembly. Water flow at this time was measured by the pressure drop on a mercury manometer across a calibrated orifice. It was found that small water flows were exceedingly difficult to maintain constant with the use of either the vertical mercury manometer or the inclined tube manometer. For this reason the procedure was altered and the use of a straight water head was adopted.

This new method incorporated the use of a small glass reservoir that could be raised or lowered at will and was connected to the water jacket of the specimen assembly by a rubber hose. The original oxygen-acetylene burner was also modified at this time to exclude atmospheric air from the flame. This change was made in an attempt to obtain a more constant combustion process.

Throughout the experiment variation in the water flow rate through the porous specimens were encountered. These variations were believed to be attributable to two major sources. First to the experimental procedure and the second to the inherent characteristics of the porous metals. In an endeavor to eliminate variations arising from the experi-

mental procedure, distilled water was used as the cooling fluid to eliminate deposits in the pores of the metal. Another difficulty in this line arose from a soot formation which covered the porous metal surface when the burner was initially lighted. This formation was completely eliminated by the use of a pipe inserted axially in the specimen assembly which shielded the porous metal surface during "light off", and was removed as soon as the flame was properly adjusted.

The variations of flow rate arising from the inherent characteristics of the porous metal are affected by water viscosity and vapor pressure which vary with the porous metal temperature. Great difficulty was encountered because of improper cooling directly above the rubber gaskets on the specimen. Formation of steam bubbles occurred in this region. In order to eliminate this condition and to keep the specimen entirely clear of steam and water vapor on its outer surface, a steam vent tube was finally installed. (See Fig. 2 and 5).

As the variations in flow rate were minimized it was found that satisfactory runs could be made and repeated. Test runs were made holding a constant inside metal surface temperature with a particular flow rate at a constant potential heat transfer. Heat transfer was varied from one run to another by changing the oxygen and acetylene pressures at the burner. In this manner the correlation of potential heat transfer and water flow rate at a constant porous metal specimen temperature was possible. The following procedure was carried out for each test run:

1. Light burner at low oxygen and acetylene pressure to insure immediate ignition.

2. Remove soot guard as soon as good combustion is obtained.

3. Adjust oxygen and acetylene pressure to desired values.

4. Use a five to ten minute warm-up period to permit the specimen to reach equilibrium at the desired temperature.

5. Make small variations in water head adjustments to maintain specimen surface temperature constant. Record data over a one inch drop of head in water reservoir.

6. Take a minimum of five such readings to insure equilibrium.

7. Record the following data for each test run.

    a. Time for one-inch drop in head,

    b. Inside surface temperature of specimen,

    c. Water inlet and outlet temperatures, and

    d. Water flow through entrant section.

Tabular data was recorded as shown in Table II.

RESULTS AND DISCUSSION

A complete summary of all experimental runs is recorded in Tables III, IV, and V. This summary was obtained from the individual test runs on the copper, bronze, and stainless steel specimens. A representative sample of such data is shown in Table II. The values listed in the summary have been corrected for flowmeter variations in accordance with the Flow Meter Correction Chart shown in Fig. 6. All experimental temperature values were taken in millivolts by means of a chromel-alumel thermocouple and potentiometer, and were converted into temperature (degrees Fahrenheit) by use of the conversion chart in Fig. 7.

All the data listed in the summary is plotted in Figs. 8 to 14 inclusive, and has been classified as to material and segregated as to temperature. These plots give a graphical presentation of heat transfer versus water flow. From the curves obtained in these figures, it was possible to plot temperature correction charts for bronze and stainless steel in the region of 180°F (Figs. 15 and 16 respectively.). These charts permit the test data taken at various temperatures to be correlated by conversion to any desired temperature.

Before beginning a detailed discussion of the individual specimens, it seems important to point out that all specimens tested were among the early porous samples produced at the Jet Propulsion Laboratory. Microphotographs of these samples showed uneven pore size and distribution. This characteristic feature of the specimens arose from the use of

ammonium bicarbonate and metal powder having comparatively large grain size. (See Table I). The irregularity of pore distribution and size caused a very noticeable unevenness of the wetted metal surface. This phenomena was apparent at low rates of water flow and was accompanied by temperature variations over the surface of the test specimen. At larger water flow rates, a uniform surface coolant film was maintained by the sweeping action of the flame on the surplus water. The use of finer grain sizes has been shown to eliminate the above mentioned difficulties. However, the perfection of this processing technique was only recently accomplished and time did not permit an investigation of any of these newer specimens.

The copper specimen was the first material upon which runs were made, and the major refinements in operating technique were developed during this period. At this time distilled water was not being used, the necessity of using a soot guard had not been realized, and the use of a steam vent tube from the water jacket had not been developed. During this period runs were made holding the water reservoir in a fixed position which amounted to a constant pressure decrease as the water level in the reservoir receded. At this time it was believed that equilibrium conditions were being closely approximated by this gradual decrease in head. As was found in later experiments, however, such procedure did not give too satisfactory a picture of the specimen at equilibrium since at least a five minute period of operation at constant head was necessary to insure an equilibrium temperature.

The runs made at decreasing heads, while defining the point of minimum pressure permissible to maintain satisfactory cooling (critical point), were of small practical use due to the transient condition of the porous metal temperature. The limited importance of this critical value is undoubtedly a function of the non-uniform pore structure, for it was found that equilibrium could not be maintained exactly at the critical point. Actually the critical point was observed in the neighborhood of 212°F., but equilibrium conditions were never held for a long time interval with temperatures much in excess of 195°F. At this lower temperature the water flow rate was increased and a complete film was formed over the surface of the porous specimen due to the sweeping action of the flame. The stability of this film could be assured only under constant water flow conditions. This even film made it possible to maintain the specimen at an equilibrium temperature. The line of investigation was, therefore, shifted to a constant specimen temperature technique as outlined in the discussion of procedure.

Only a relatively few number of runs of this new type were made on the copper specimen due to the deterioration of the metal caused by corrosion and clogging. For this reason the data on the copper specimen is limited to only a few points and accounts for the meager amount of data on the copper specimen as plotted in Fig. 8.

At this time a bronze specimen was completed and tests were made using the constant specimen temperature technique throughout. Three inside surface temperatures covering the most appropriate operating range (175° to 190°F) were selected. This range of temperature was

found to be the most appropriate for practical use since it was difficult to maintain equilibrium temperatures in excess of these values. Equilibrium temperatures under this range were satisfactory for operation but necessitated an increasing volume of coolant and would be of small practical interest. The data taken on the bronze specimen gave smooth consistent curves which were duplicated for long continuous operation and on successive days. The small variations that were still apparent were believed to have arisen from vapor clogging of the porous metal. From the curves obtained, the temperature correction chart (Fig. 15) was constructed which may be used to standardize data taken at any equilibrium temperature.

During the testing of the bronze metal, a thermocouple was installed on the outer surface of the test specimen adjacent to the water jacket. The results showed a temperature gradient of approximately 50°F existing across the porous metal wall. This type of test was carried out for several experimental runs and the temperature difference was of the order shown in Fig. 17.

A similar method was used in the investigation of a stainless steel specimen, from which a correction chart was formulated in a like manner. Stainless steel specimens are very difficult to process and the sintering operation of this sample was carried out in a slightly oxidizing atmosphere with resulting formation of chromium oxide. Refinements in the processing of stainless steel are being attained; however further specimens were not available at this time. Therefore the stainless steel porous specimen used showed a greater tendency to

become clogged due to the presence of small particles of chromium oxide throughout the specimen. For this reason it is believed that the final data taken at 179°F for this specimen may be only qualitative.

The actual value of heat transfer at the specimen could not be measured, therefore potential heat transfer values were obtained by determining the heat transfer at the water jacket immediately ahead but adjacent to the test section. This heat transfer was determined by measuring the temperature rise and flow rate of the water surrounding the entrant section. Heat transfer values were recorded in BTU/in.^{2}-sec and were obtained by use of the equation:

$$Q = \frac{8.3}{60} \times f \times \frac{\Delta T}{A}$$

Where:

Q = heat transfer (potential heat transfer) (BTU/in.2- sec)

f = coolant jacket water flow rate (gal/min)

ΔT = inlet-outlet temperature difference (oF)

A = cylindrical surface area of entrant section (in.2) (Section a - b, Fig. 2)

Water flow rate through the porous specimen was determined in cc/in.^{2}- sec from the following formula:

$$q = \frac{A_r \times \Delta h_r \times (2.54)^3}{A_s \times 60 \times t} = \frac{0.0775}{t}$$

Where:

q = water flow rate (cc/in.^{2}- sec)

t = time (min)

A_r = reservoir cross sectional area (1.63 in.^{2})

Δh_r = drop in reservoir head (1 in.)

A study of the graphical results show curves of a similar type for all specimens with slight variations of slope. The results indicate that a porous stainless steel specimen can be cooled with slightly less water flow than for a copper or bronze specimen. However, it must be emphasized that the test specimens were not exactly similar in pore size and distribution and no conclusions of a quantitative nature should be made from these tests. The amount of water required for sweat cooling appears to be only slightly affected by the metal conductivity. This is brought out by the similarity of the curves for stainless steel and copper which have a variation in thermal conductivity of approximately thirteen. It is therefore concluded that heat transfer is mainly a function of water flow and at most is only slightly affected by the thermal conductivity of the metal.

The results obtained in these experiments are of a qualitative nature. Small variations in flow rate were found to give large temperature differences. As soon as specimens of finer porosity become available a much more uniform wetted surface can be obtained. By using a finer porosity of this nature, larger pressure heads could be used in cooling. It is felt that the use of higher pressures will minimize the difficulties that arose from clogging due to water vapor.

In spite of the fact that these results are only qualitative, they show definitely that the "sweat cooling" process is highly feasible. Continued operations were made with specimens in contact with a flame whose temperature was of the order of 3500°F and the temperatures of the

sweat cooled metals could be maintained around 185°F with a relatively small amount of water flow. This is shown graphically in Figs. 15 and 16 where a potential heat transfer of 1 BTU/in.^{2}- sec was handled with a water flow rate of approximately 0.1 cc/in.^{2}-sec.

CONCLUSIONS

From the results of this investigation, the following conclusions can be drawn:

1. Water flow rate is a primary factor in maintaining sweat cooled metals at equilibrium temperatures.
2. The porous metal conductivity has small effect on the potential heat transfer of a sweat cooled metal.
3. Sweat cooled porous metals will withstand gas temperatures two to three times larger than the temperatures used in present day turbojet units.
4. A potential heat transfer of 1 BTU/in.^{2}-sec may be handled by sweat cooling with a water flow rate of approximately 0.1 cc/in.^{2}- sec.

RECOMMENDATIONS

In view of the results obtained, the authors submit the following recommendations:

1. That similar investigations be conducted to determine the effect caused by: a) pore size, and b) percent porosity.
2. A more detailed analysis of the effects of flame velocity and temperature upon sweat cooling.
3. The sealing gaskets on the porous metal specimens should be placed on the ends of the test specimen in order to eliminate steam formation in the water jacket as encountered in this study.

DESCRIPTION AND SPECIFICATION OF POROUS METAL SAMPLES

Copper Specimen

90% Copper Powder of screen analysis

35 - 60	60 - 100	100 - 150	150 - 200	200 - 325	325 -
28.8	55.2	10.2	1.3	1.6	2.2

10% Ammonium Bicarbonate which all passed through a screen of size 80.

Metal Compacted at 40,000 lb/in.^{2}

Sintered at 1600°F for 2 hours in a Hydrogen atmosphere.

Bronze Specimen

90% Copper and Tin Powder in ratio of 9 to 1.

Copper screen analysis

35 - 60	60 - 100	100 - 150	150 - 200	200 - 325	325 -
0	Trace	Trace	23	26.4	49.8

Tin screen analysis

35 - 60	60 - 150	150 - 325	325 -
0	2.0	3.0	95

10% Ammonium Bicarbonate same as above.

Metal Compacted at 40,000 lb/in.^{2}

Sintered at 1400°F for 2 hours in a Hydrogen atmosphere.

18 - 8 Stainless Steel Specimen

90% 18 - 8 Stainless Steel Powder of screen analysis

DESCRIPTION AND SPECIFICATION OF POROUS METAL SAMPLES

Copper Specimen

90% Copper Powder of screen analysis

35 - 60	60 - 100	100 - 150	150 - 200	200 - 325	325 -
28.8	55.2	10.2	1.8	1.6	2.2

10% Ammonium Bicarbonate which all passed through a screen of size 80.

Metal Compacted at 40,000 lb/in.^{2}

Sintered at 1600°F for 2 hours in a Hydrogen atmosphere.

Bronze Specimen

90% Copper and Tin Powder in ratio of 9 to 1.

Copper screen analysis

35 - 60	60 - 100	100 - 150	150 - 200	200 - 325	325 -
0	Trace	Trace	23	26.4	49.8

Tin screen analysis

35 - 60	60 - 150	150 - 325	325 -
0	2.0	3.0	95

10% Ammonium Bicarbonate same as above.

Metal Compacted at 40,000 lb/in.^{2}

Sintered at 1400°F for 2 hours in a Hydrogen atmosphere.

18 - 8 Stainless Steel Specimen

90% 18 - 8 Stainless Steel Powder of screen analysis

TABLE I
Contd.

36 - 60	60 - 100	100 - 150	150 - 200	200 - 325	325 -
Trace	1.2	5.2	7.0	24.4	62.0

10% Ammonium Bicarbonate same as above.

Metal Compacted at 30,000 lb/in.^{2}

Sintered at 1800°F for 2 hours in a Helium atmosphere.

SAMPLE DATA SHEET

Stainless Steel Specimen

Run #210

Oxygen Pressure 30 lb/in.^{2}

Acetylene Pressure 8 lb/in.^{2}

Time	Potentiometer Readings			Flow Rate
	Specimen (Inside Surface)	Entrant Water (Inlet)	Entrant Water (Outlet)	
Sec.	millivolts	millivolts	millivolts	Gal/Min
0	4.00	1.48	3.62	.490
36	4.02	1.48	3.58	.485
0	4.00	1.48	3.60	.485
36.3	4.00	1.48	3.58	.490
0	4.00	1.48	3.56	.490
37.3	4.02	1.48	3.58	.490
0	4.00	1.48	3.58	.490
37.0	4.00	1.48	3.62	.490
0	4.00	1.48	3.58	.490
36.6	4.00	1.48	3.60	.490
Average 36.6	4.00	1.48	3.59	.489

SUMMARY OF COPPER DATA

Run Number	Specimen		Potential Heat Transfer
	Flow Rate	Wall Temp.	
	c.c./in.^{2} sec.	^{o}F	BTU/in.^{2} sec.
1	.0535	165	.290
2	.0625	168	.415
3	.0755	160	.476
4	.0755	167	.550
5	.1070	166	.589
6	.0328	191	.318
7	.0395	191	.431
8	.0348	197	.490
9	.0362	197	.471
10	.0390	197	.452

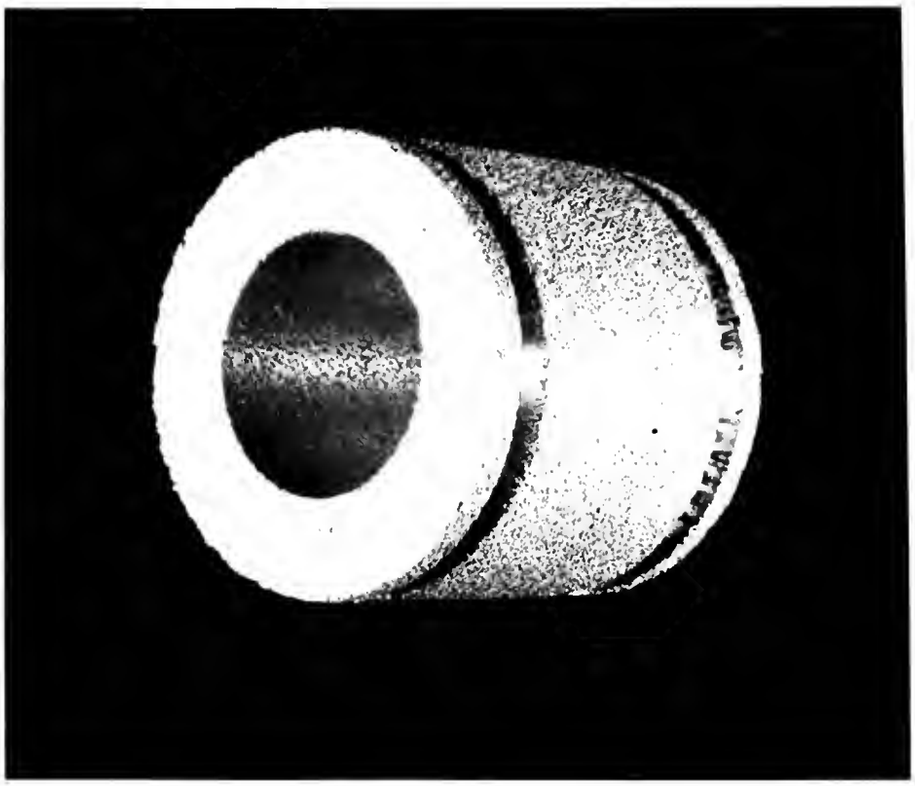
SUMMARY OF BRONZE DATA

Run Number	Specimen		Potential Heat Transfer
	Flow Rate	Wall Temp.	
	$cc/in.^2 sec$	^oF	$BTU/in.^2 sec$
101	.0895	175	.713
102	.1025	175	.786
103	.120	175	.803
104	.0992	175	.637
105	.1048	175	.828
106	.555	175	.606
107	.475	183	.426
108	.0705	182	.699
109	.1095	180	.933
110	.1295	180	1.065
111	.122	181	1.090
112	.0683	186	.842
113	.0981	188	1.032
114	.0392	187	.564
115	.056	187	.775
116	.091	188	.996
117	.0391	187	.590
118	.0423	186.5	.578
119	.0506	188	.774
120	.0675	187	.837
121	.0894	188	1.091

SUMMARY OF STAINLESS STEEL DATA

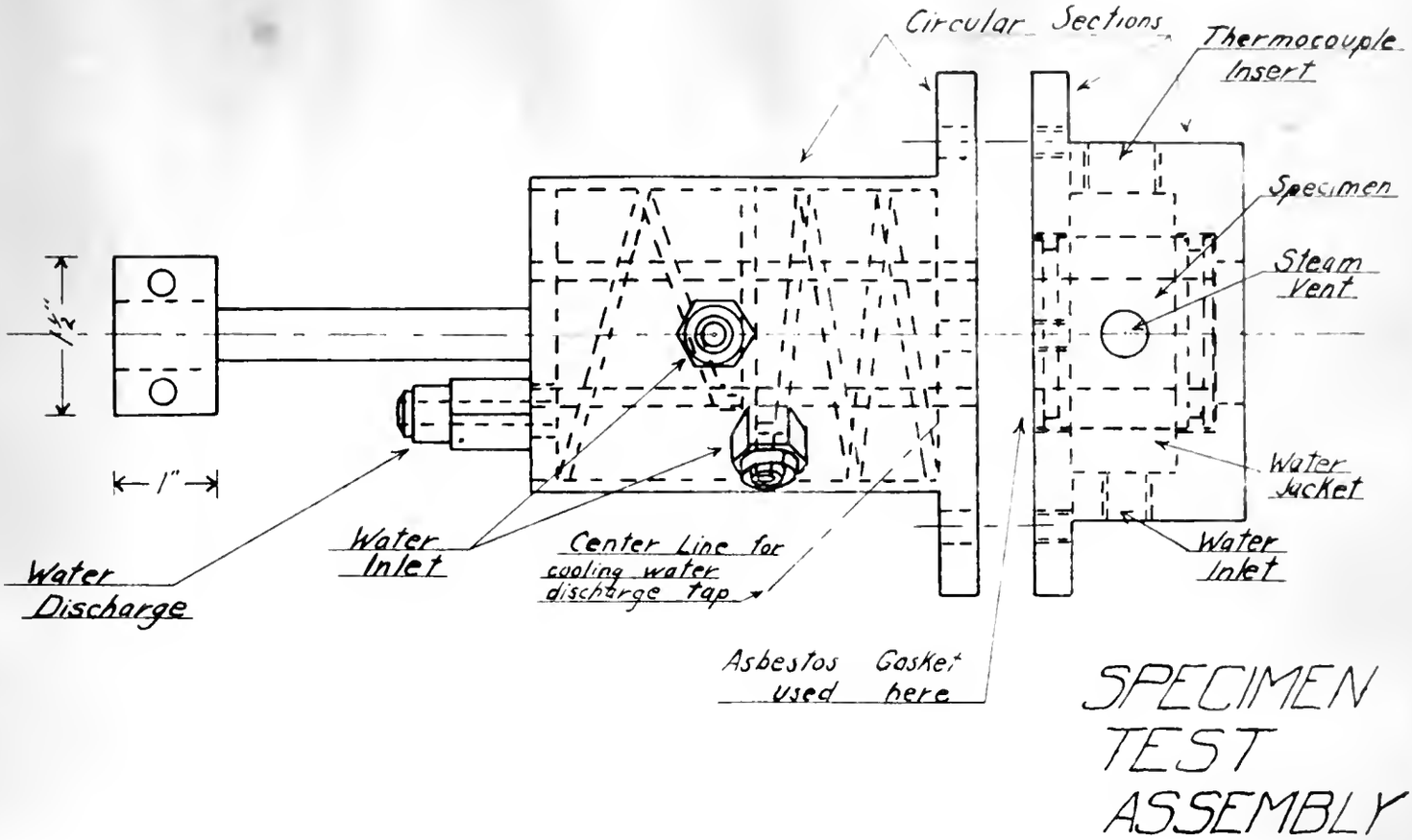
Run Number	Specimen		Potential Heat Transfer
	Flow Rate	Wall Temp.	
	$cc/in.^2$ sec	^oF	$BTU/in.^2$ sec
201	.0517	179	.531
202	.0619	179	.740
203	.0753	179	.894
204	.0823	179	.884
205	.0662	179	.756
206	.0740	179	.612
207	.0884	179	.795
208	.0982	179	.803
209	.1090	179	.915
210	.127	179	1.038
211	.0395	179	.477
212	.0383	184	.6125
213	.0380	184	.586
214	.0600	184	.758
215	.0662	184	.758
216	.0713	184	.890
217	.1030	184	.962
218	.02855	184	.436
219	.0692	186	1.001
220	.0303	187	.619
221	.0379	187	.640

222	.0445	187	.765
223	.0507	187	.913
224	.0699	187	1.010
225	.0742	187	1.055
226	.0368	187	.604
227	.0530	186	.930

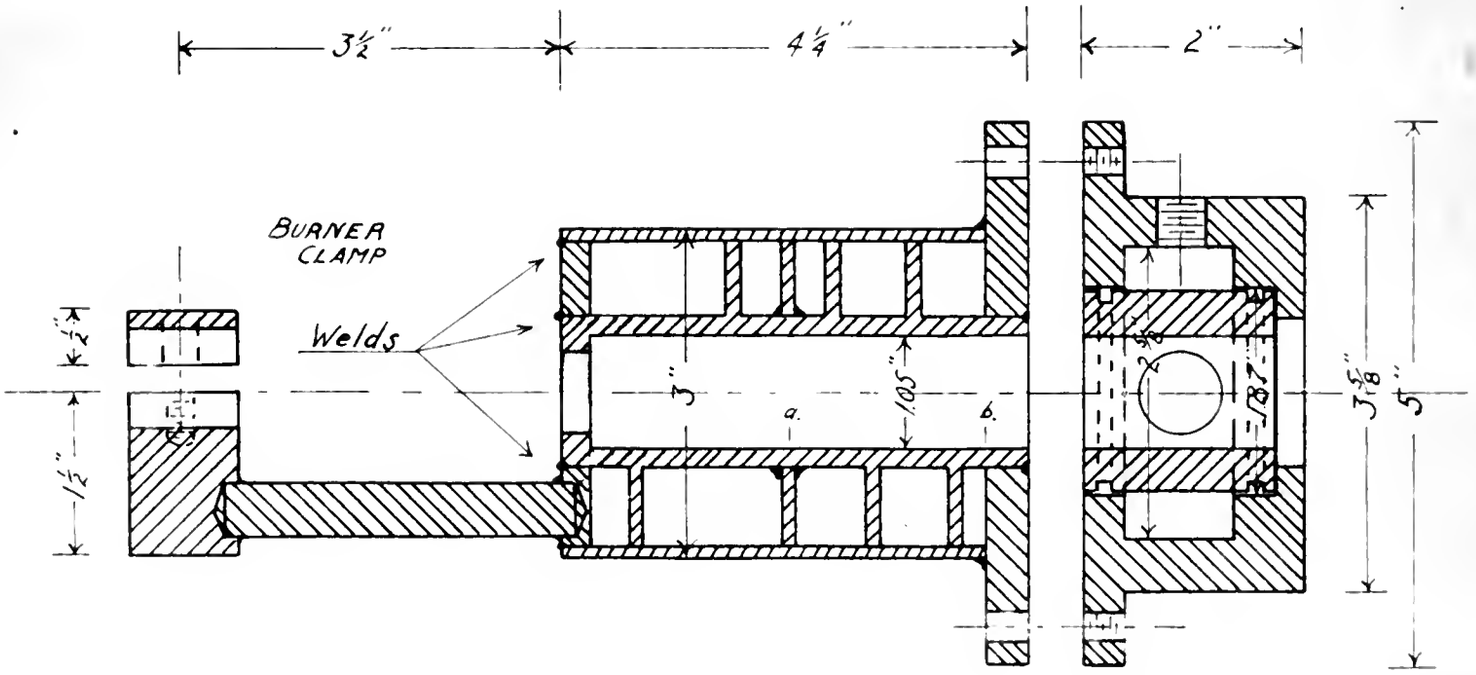


Porous Metal Test Specimen

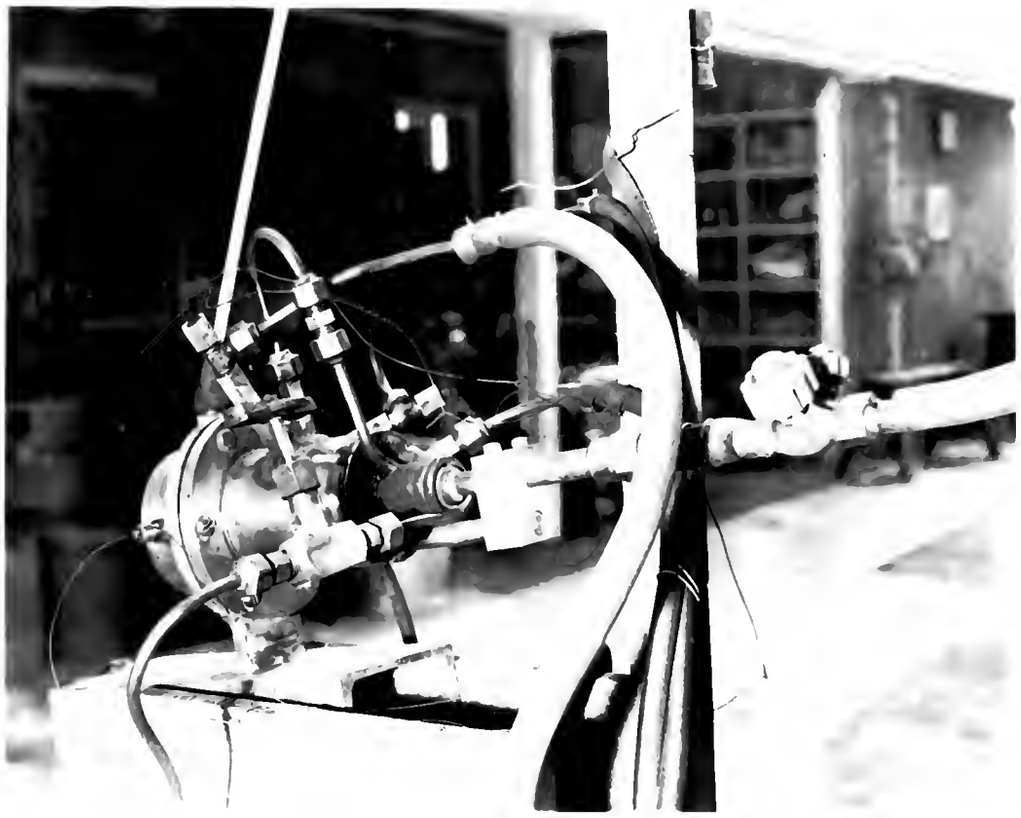
FIG. 2



SPECIMEN TEST ASSEMBLY

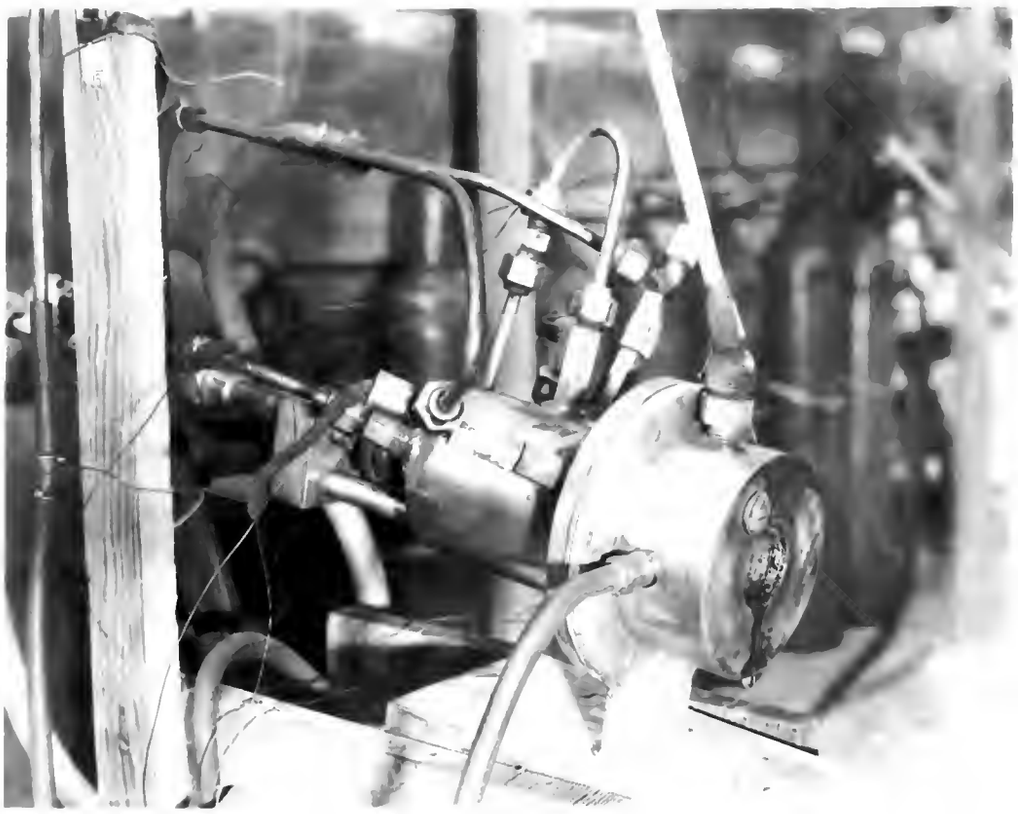


ENTRANT SECTION SPECIMEN HOLDER



Specimen Test Assembly (Rear Angle View)

Complete Experimental Test Assembly



Specimen Test Assembly (Front Angle View)

RESTRICTED

FIG 6

FLOW METER CORRECTION CHART

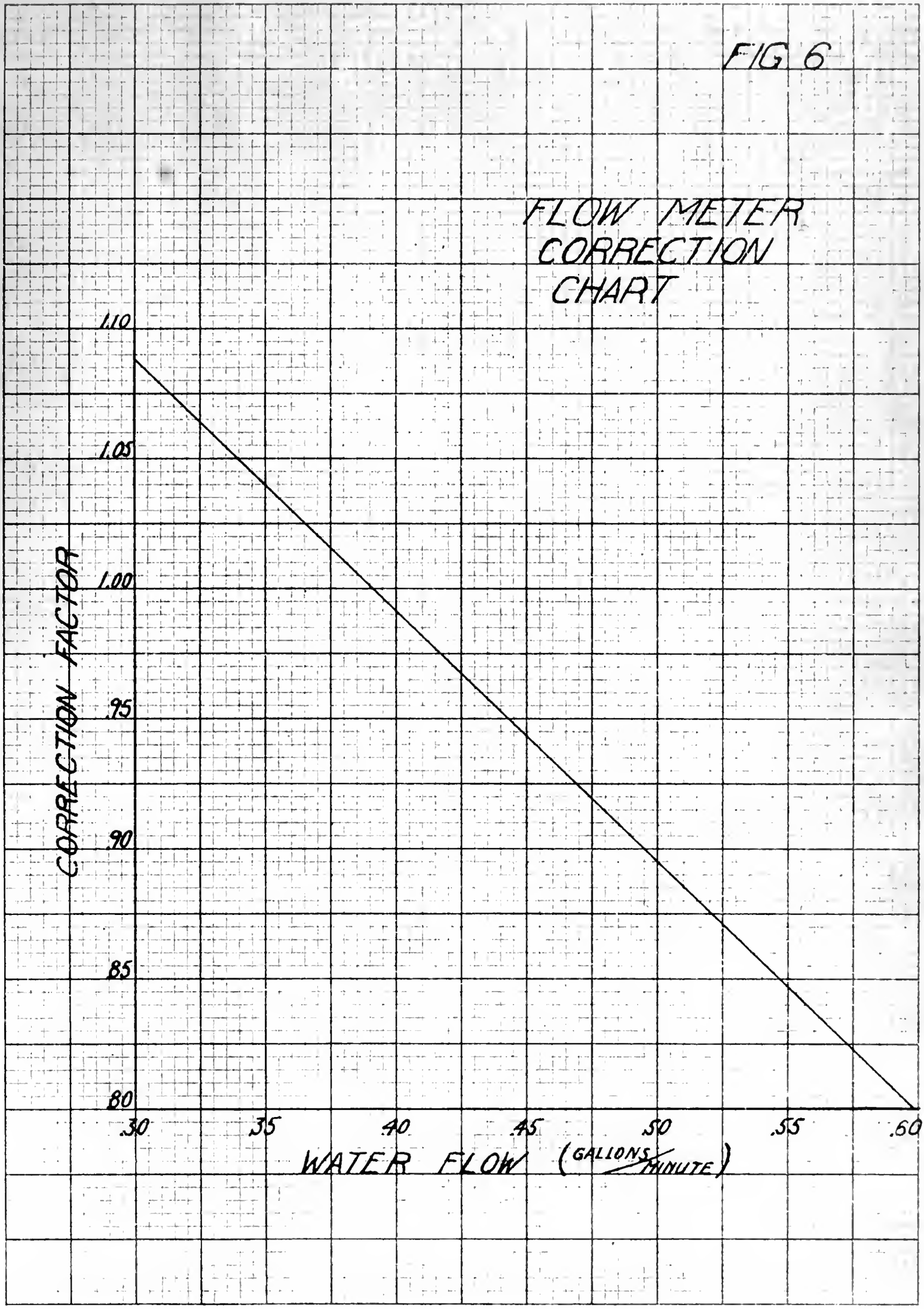


FIG. 7

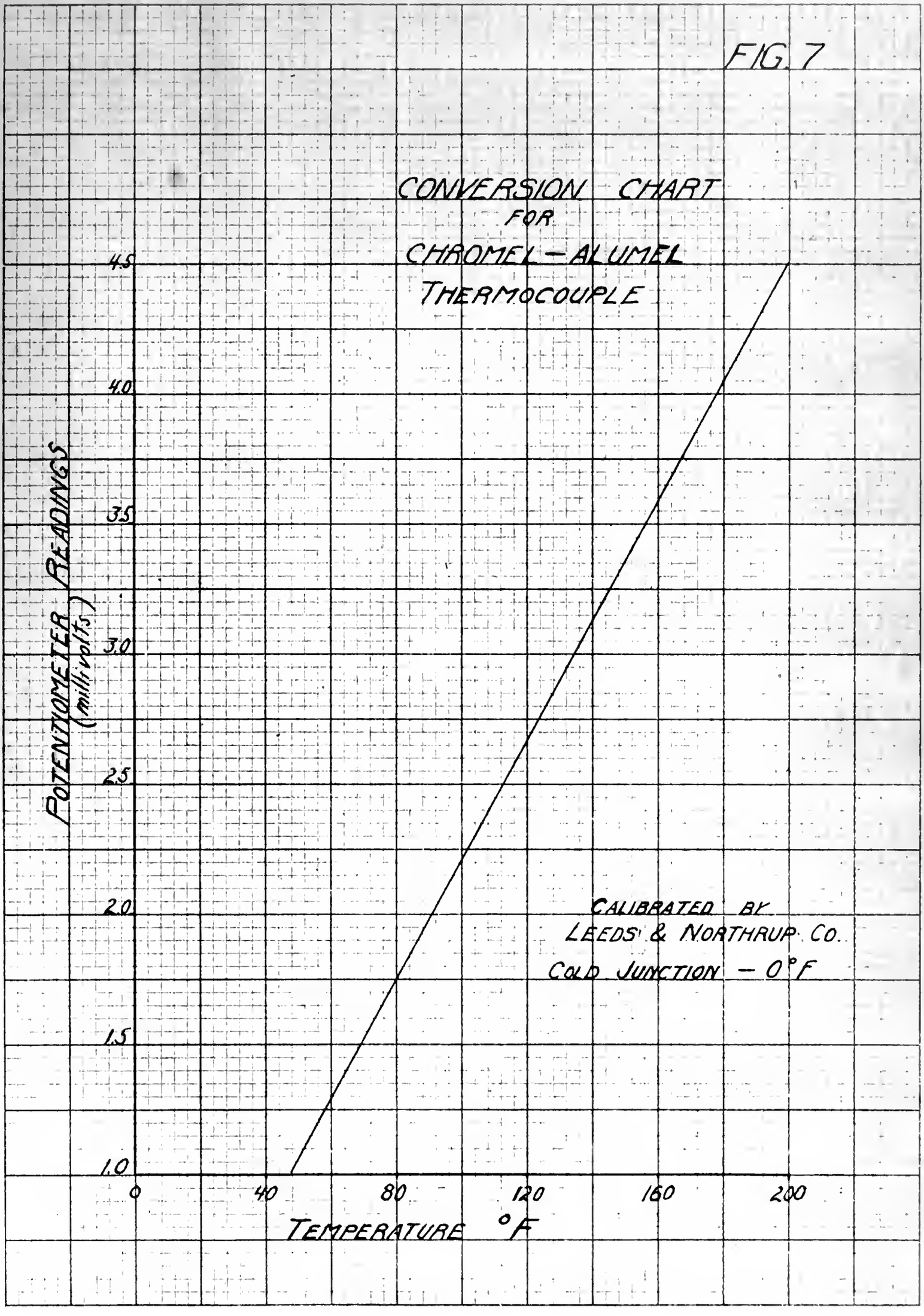

CONVERSION CHART
FOR
CHROMEL – ALUMEL
THERMOCOUPLE
POTENTIOMETER READINGS
(millivolts)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
40
80
120
160
200
TEMPERATURE °F
CALIBRATED BY
LEEDS & NORTHRUP CO.
COLD JUNCTION – 0°F

FIG. 8

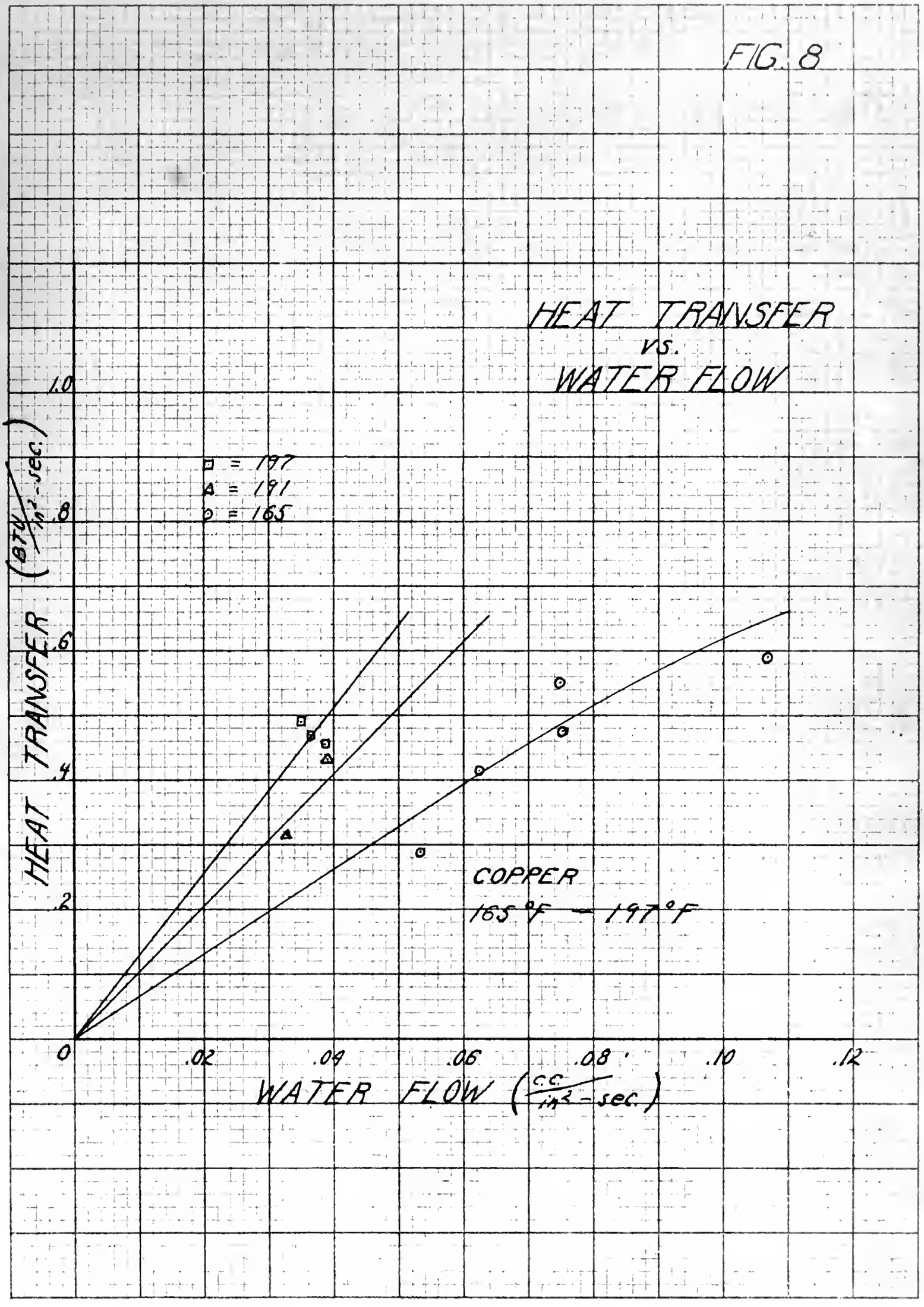

HEAT TRANSFER
vs.
WATER FLOW
□ = 197
△ = 191
○ = 165
COPPER
165 °F — 197 °F
HEAT TRANSFER (BTU/in²-sec.)
1.0
.8
.6
.4
.2
0
.02
.04
.06
.08
.10
.12
WATER FLOW (c.c./in²-sec.)

FIG. 9

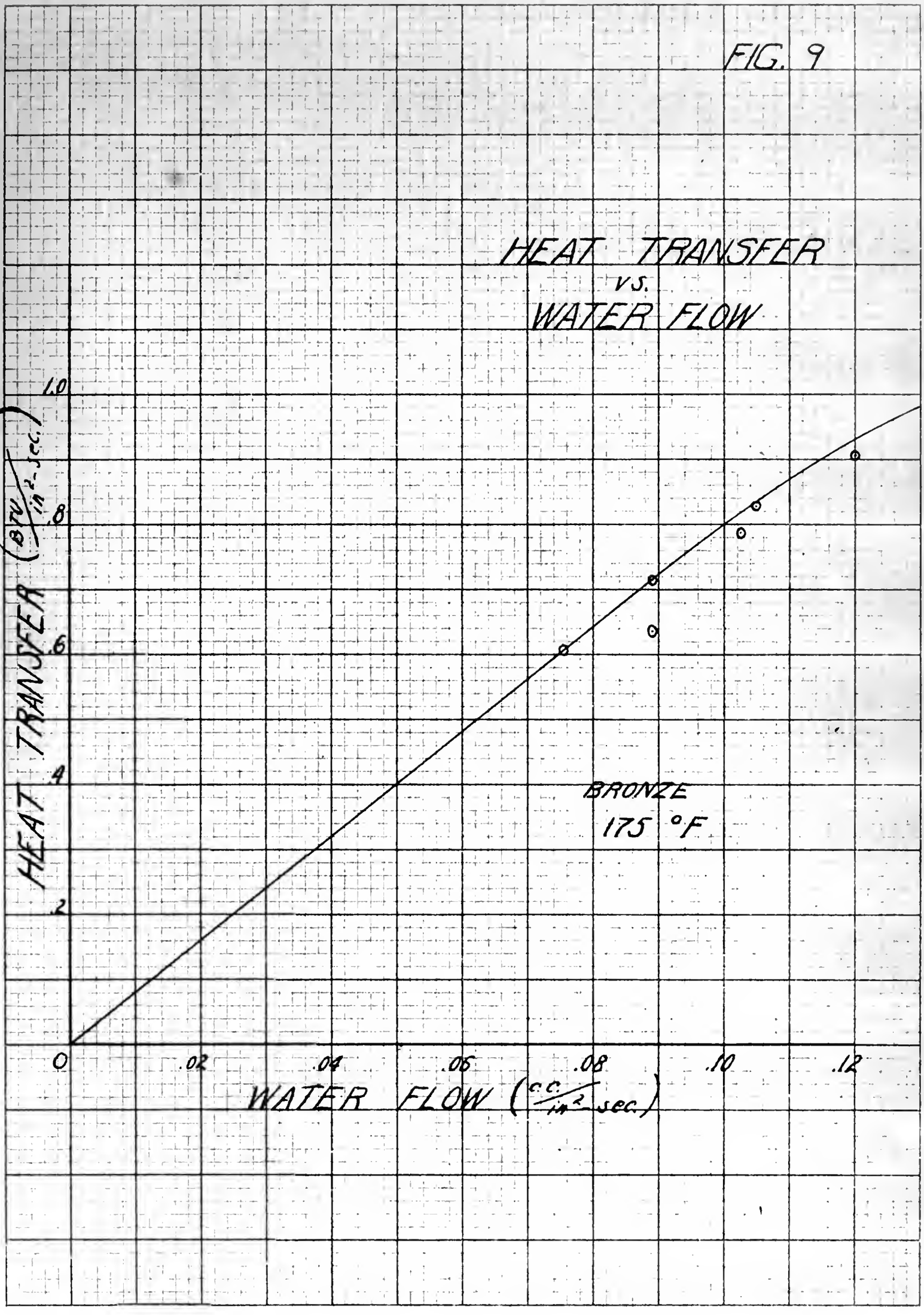

HEAT TRANSFER
VS.
WATER FLOW
HEAT TRANSFER (BTU/in²-sec.)
1.0
.8
.6
.4
.2
0
.02
.04
.06
.08
.10
.12
WATER FLOW (c.c./in²-sec.)
BRONZE
175 °F

FIG. 10

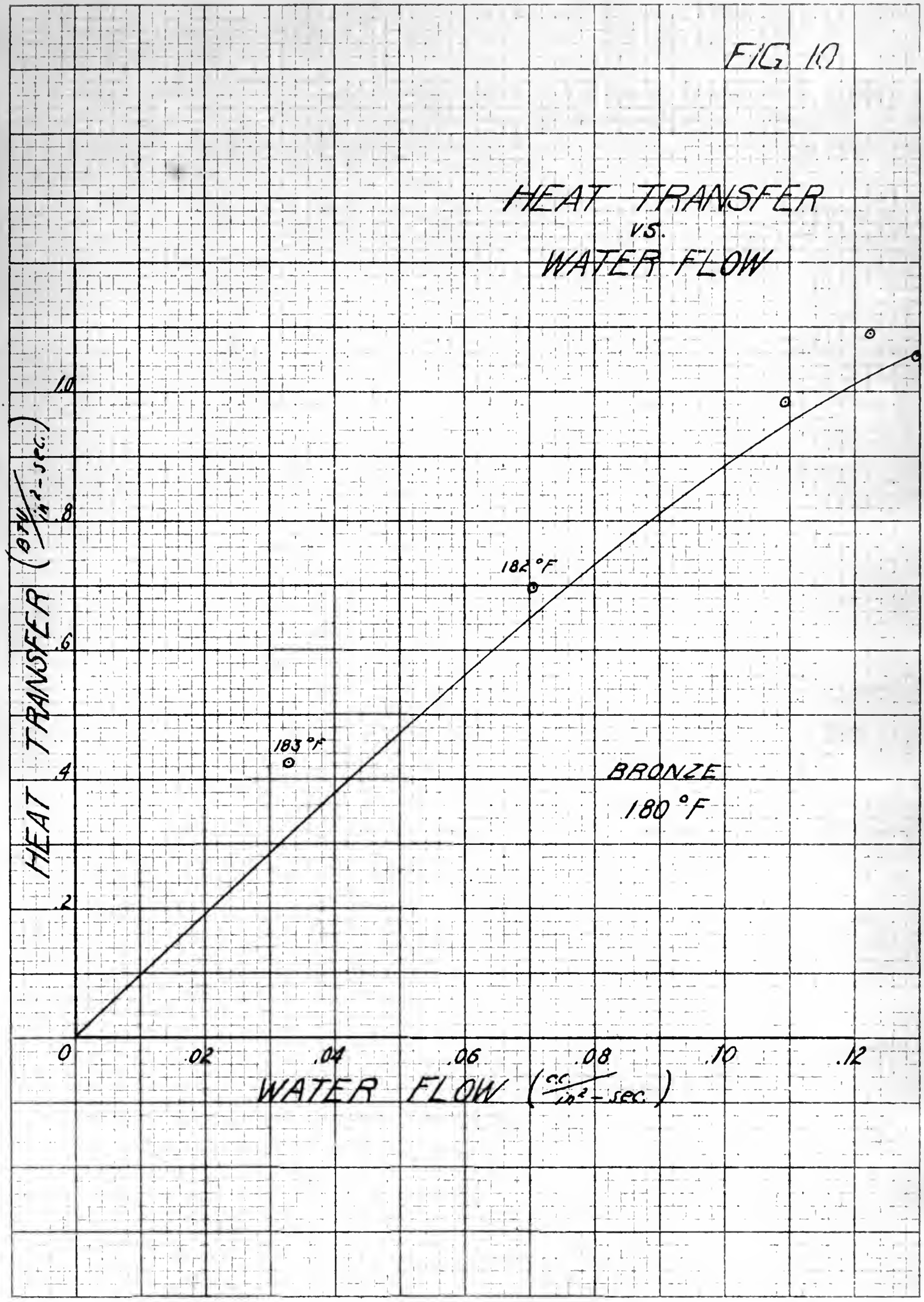

HEAT TRANSFER
VS.
WATER FLOW
HEAT TRANSFER (BTU/in²-sec.)
1.0
.8
.6
.4
.2
0
182 °F
183 °F
BRONZE
180 °F
.02
.04
.06
.08
.10
.12
WATER FLOW (cc/in²-sec.)

FIG. 11

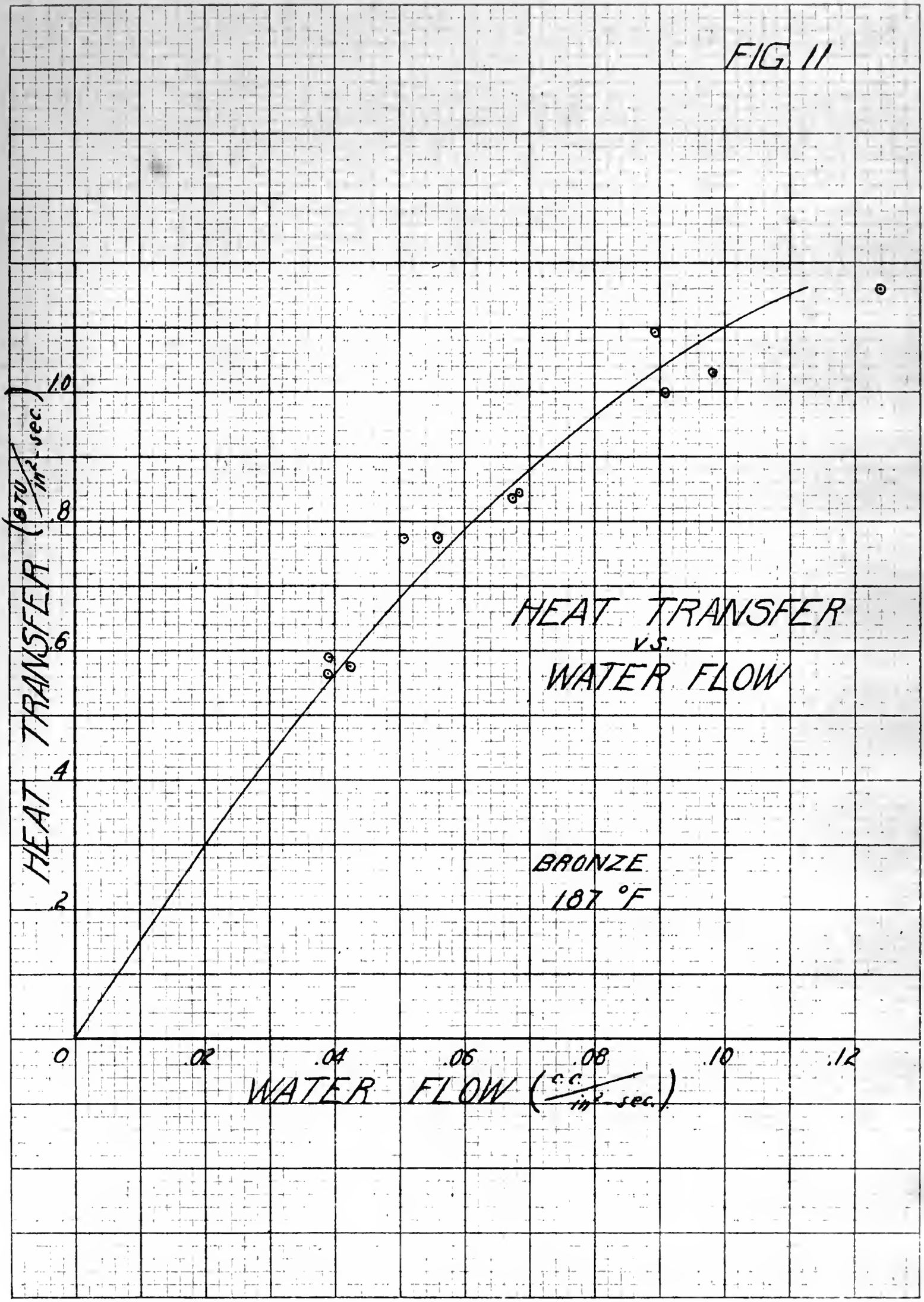

HEAT TRANSFER (B.T.U. / in² - sec.)
1.0
.8
.6
.4
.2
0
.02
.04
.06
.08
.10
.12
WATER FLOW (c.c. / in² sec.)
HEAT TRANSFER
V.S.
WATER FLOW
BRONZE
187 °F

FIG 12

HEAT TRANSFER vs. WATER FLOW

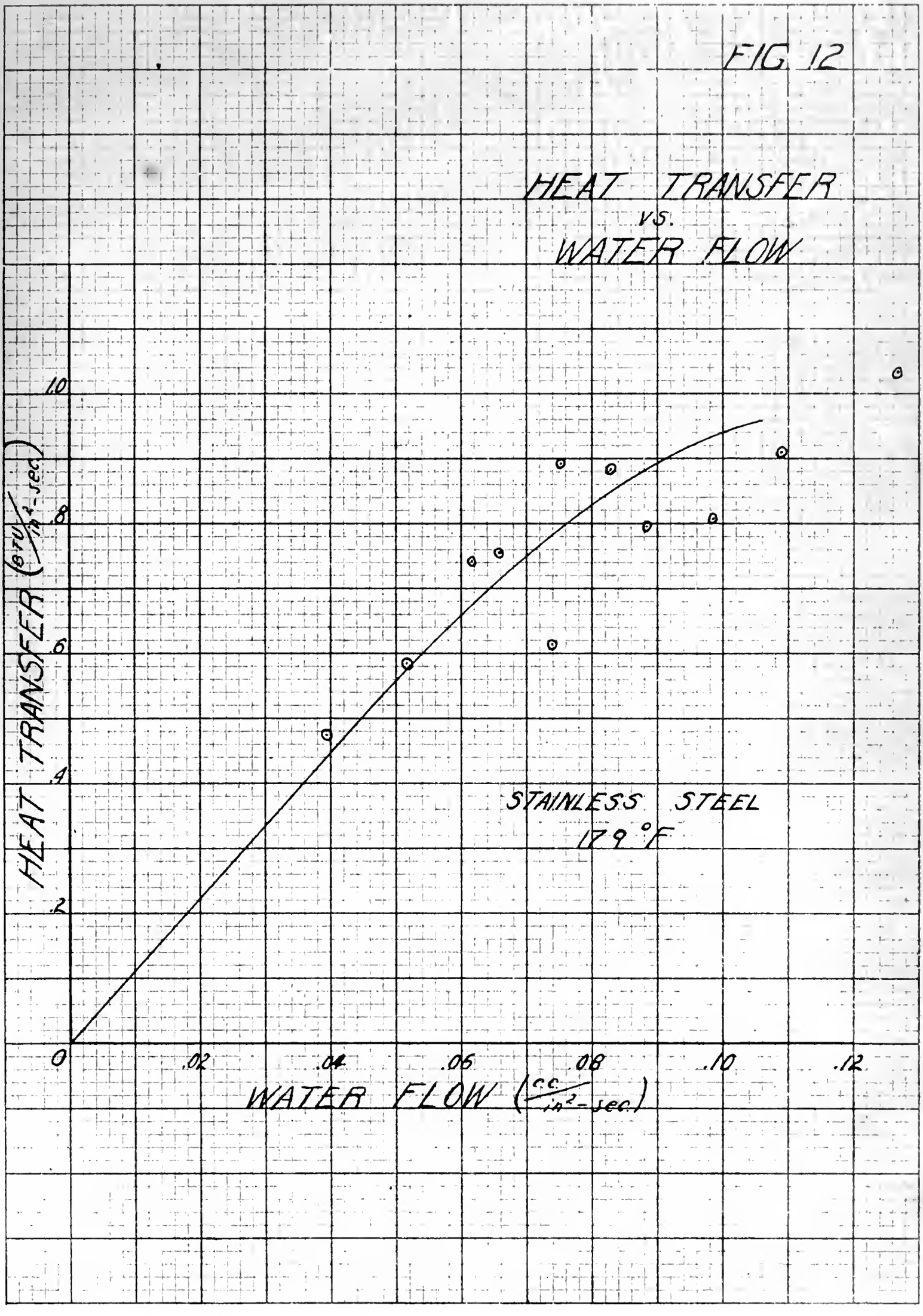


FIG 13

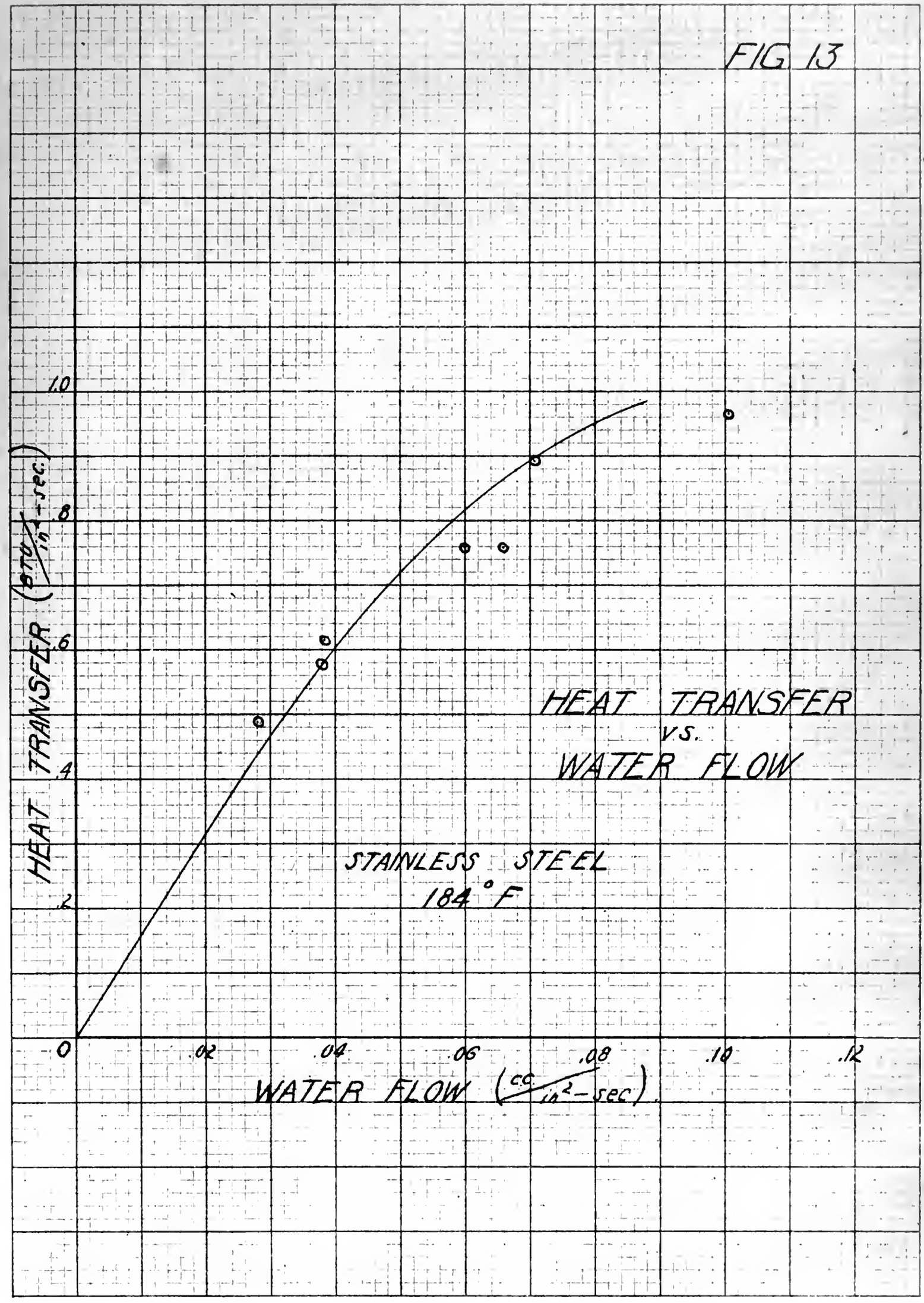

HEAT TRANSFER (BTU/in²-sec)
1.0
.8
.6
.4
.2
0
.02
.04
.06
.08
.10
.12
WATER FLOW (cc/in²-sec)
HEAT TRANSFER
VS.
WATER FLOW
STAINLESS STEEL
184° F

FIG 14

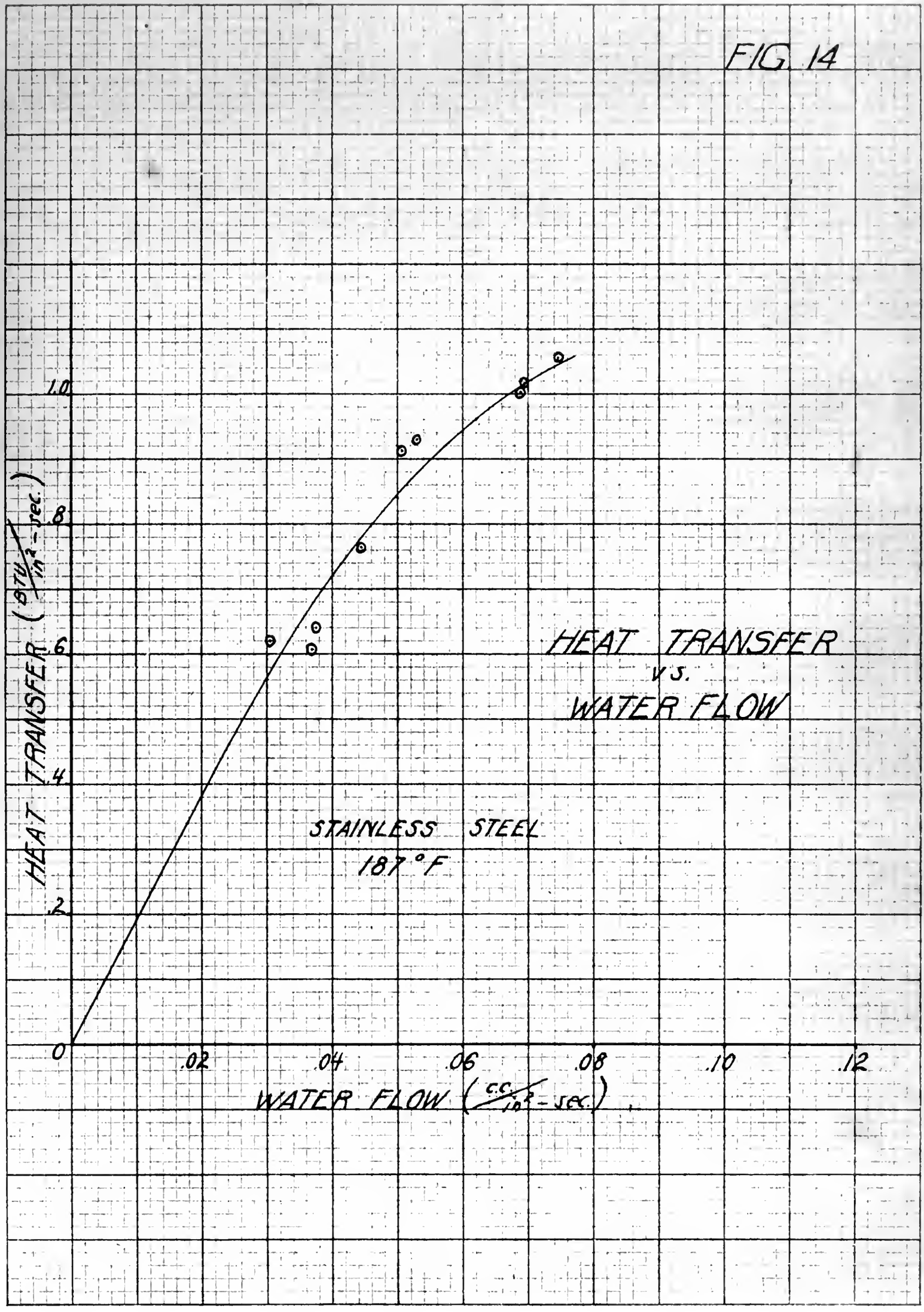

HEAT TRANSFER
VS.
WATER FLOW
STAINLESS STEEL
187°F
HEAT TRANSFER (BTU/in² - sec.)
WATER FLOW (c.c./in² - sec.)
0
.2
.4
.6
.8
1.0
.02
.04
.06
.08
.10
.12

FIG. 15

TEMPERATURE CORRECTION CHART FOR BRONZE

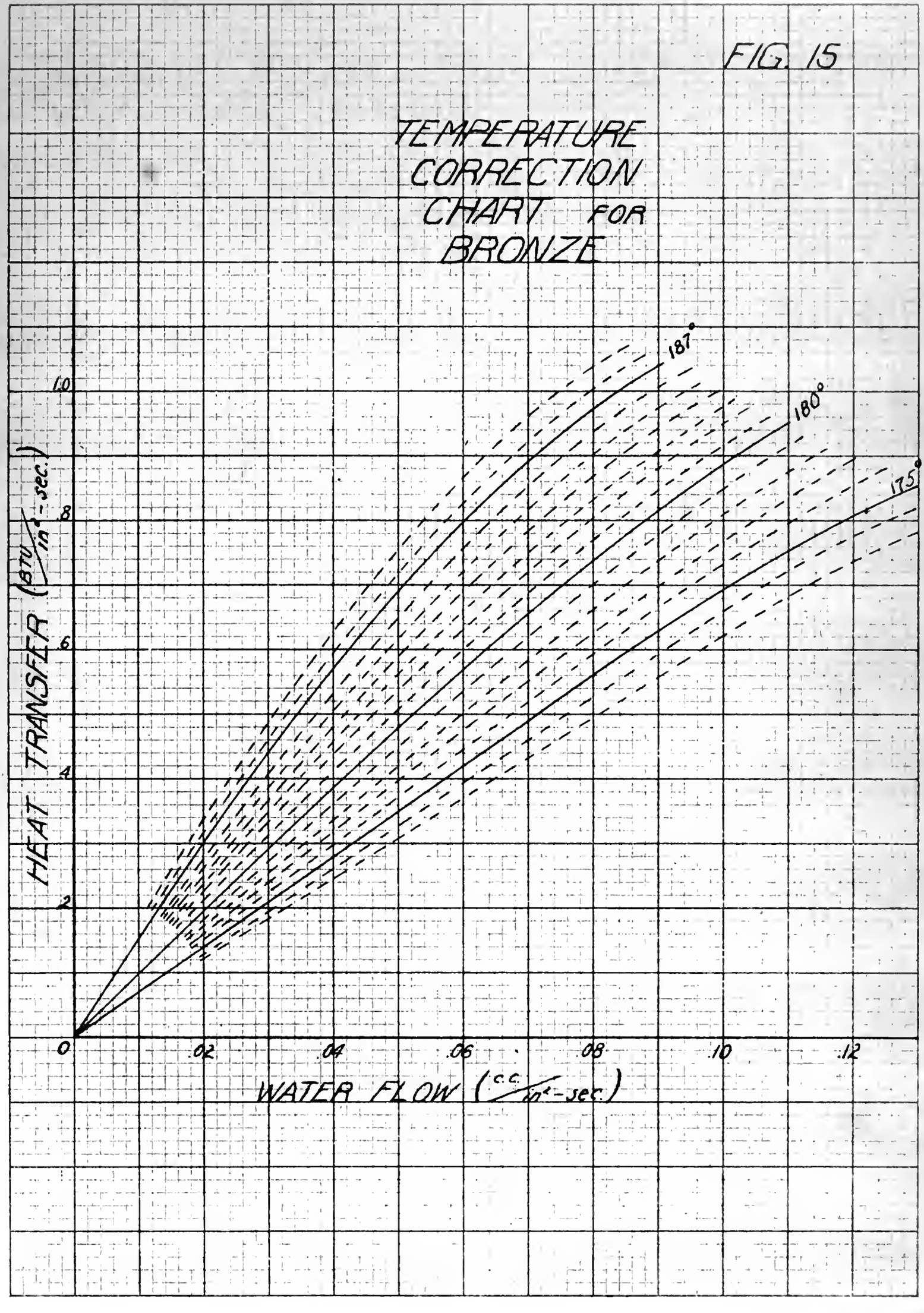


FIG 16

TEMPERATURE CORRECTION CHART FOR STAINLESS STEEL

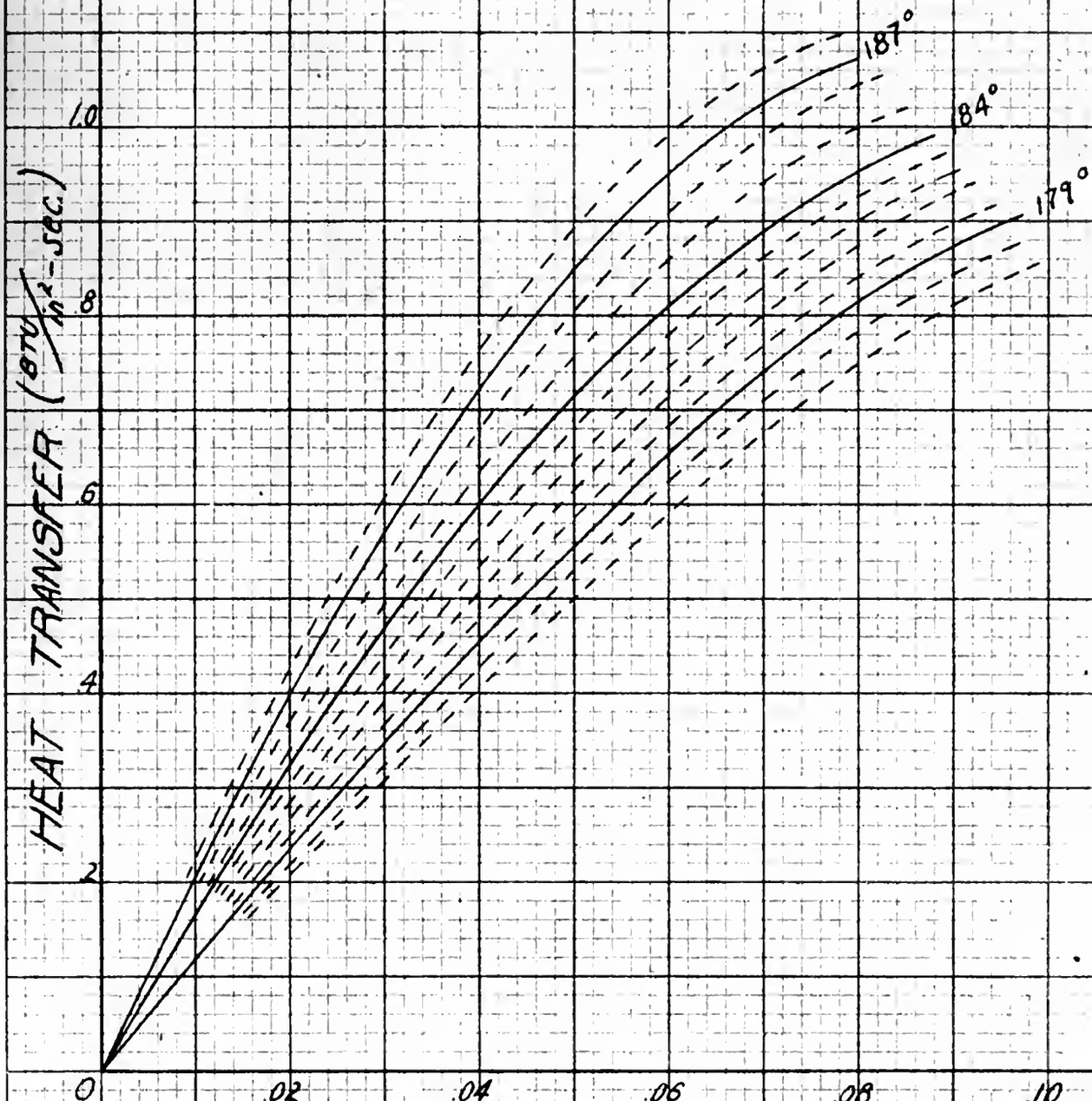
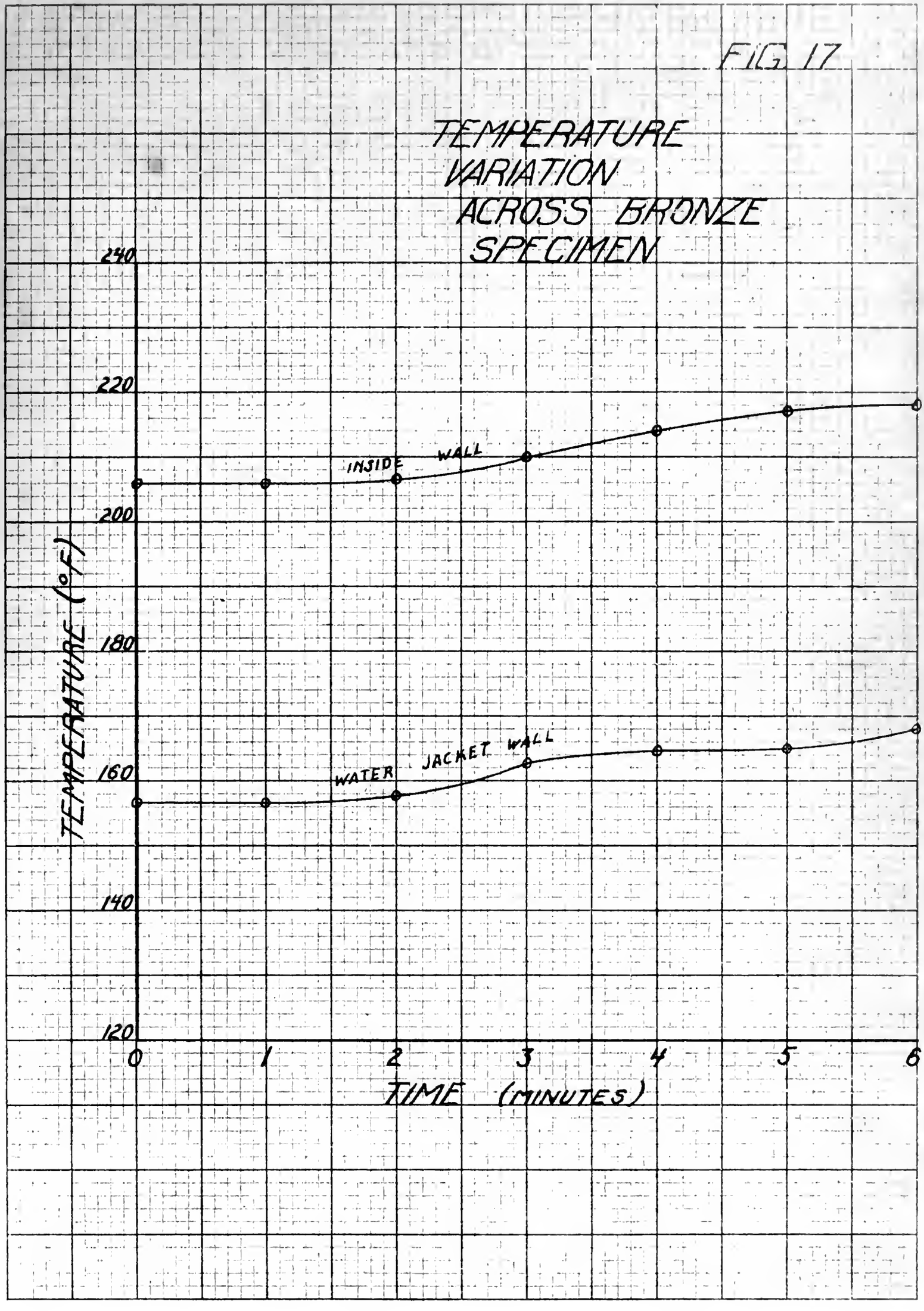


FIG 17

TEMPERATURE VARIATION ACROSS BRONZE SPECIMEN



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